RGNZ/MGPB

Application of GIS technology in management of brownfield sites containing NORM residues

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
DOI: 10.17794/rgn.2025.4.9

Original scientific paper

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Abstract

Since "brownfield sites" (BFS) are one of main environmental engineering challenges, countries in the European Union are obligated to consider their management. One of the main tools for BFS management is geographic information system (GIS) technology on two levels: representation of all BFS in the country and representation of material/pollutant distribution (surface, amount and concentrations, etc.) for the respective sites. The Republic of Croatia has several brownfield sites, including the site of the decommissioned factory of plastics and chemical products, Jugovinil, in the city of Kaštela, Croatia, as a significant example. The decommissioned chemical plant and its coal powered powerplant caused the contamination of the industrial site with heavy metals and naturally occurring radioactive materials (NORM) residues. Since the decommissioning of the factory, other, small-scale industrial activities (shipyards) caused the site's additional contamination. This BFS has several locations containing a total of 552,101.29 m^3 of different types of deposited material (coal ash and slag, brought in soil material, construction waste, etc.), of which ≈ 240.893 m^3 are relevant for this research. The research presented here is based upon studies done in 2010-2011. Since the research data is overwhelmingly large, only part of it represented in this paper: measurements of three radionuclide concentrations from the ^{232}Th decay chain. The computer GIS software *ArcGIS Pro* was used to create maps showing concentrations of radioisotopes, which enabled the identification of hotspots and potential sources of pollution. The interpolation was performed using the geostatistical method Empirical Bayesian Kriging. Recommended actions for the management of this location include remediation and caveat concerning urbanisation of the site.

Keywords:
brownfield, NORM residues, radionuclides, GIS

1. Introduction

Brownfield sites are, by definition, large-scale industrial and infrastructure abandoned sites, and they include abandoned: "built sites" (urbanised areas), industrial sites, military complexes and constructions, etc. (**Anderson et al., 2001; Brebbia & Mander, 2006; Hollander et al., 2010; Syms, 2012; Dulić & Krklješ, 2013; Obaje et al., 2019; Zheng & Masrabaye, 2023**). The range of impact on the environment for different brownfield sites varies, depending on the size of the site and the material it contains:

- *Abandoned urban objects/areas* – usually containing old and ruined constructions and/or construction waste, remaining fuel storage places, etc.
- *Landfills and other repositories of waste* – both those that function without effects on the environment and those that have undesired effects on the environment, usually due to poor design or construction. Even if the landfill of solid municipal waste or the repository (disposal site) of other types of wastes is functioning without effects on the environment, the location is "lost for good", since there cannot be reutilisation of the site for any other purpose.
- *Locations contaminated during the transport of hazardous materials* – usually due to hydrocarbon spillages, leaks of solvents, pesticides, and other liquid materials or spillage of other solid form contaminants, usually in form of dust (dust particles range in size from 1 to 400 μm).
- *Abandoned military sites* – readily including various types of contaminants and hazardous materials and constructions or construction waste, which can also be contaminated. Pollutants on these sites vary from remaining explosives and unused ammunition, fuels and lubricants, radioactive materials, municipal waste, chemical waste, medical waste, etc.

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Received: 6 February 2025. Accepted: 7 March 2025.
Available online: 27 August 2025

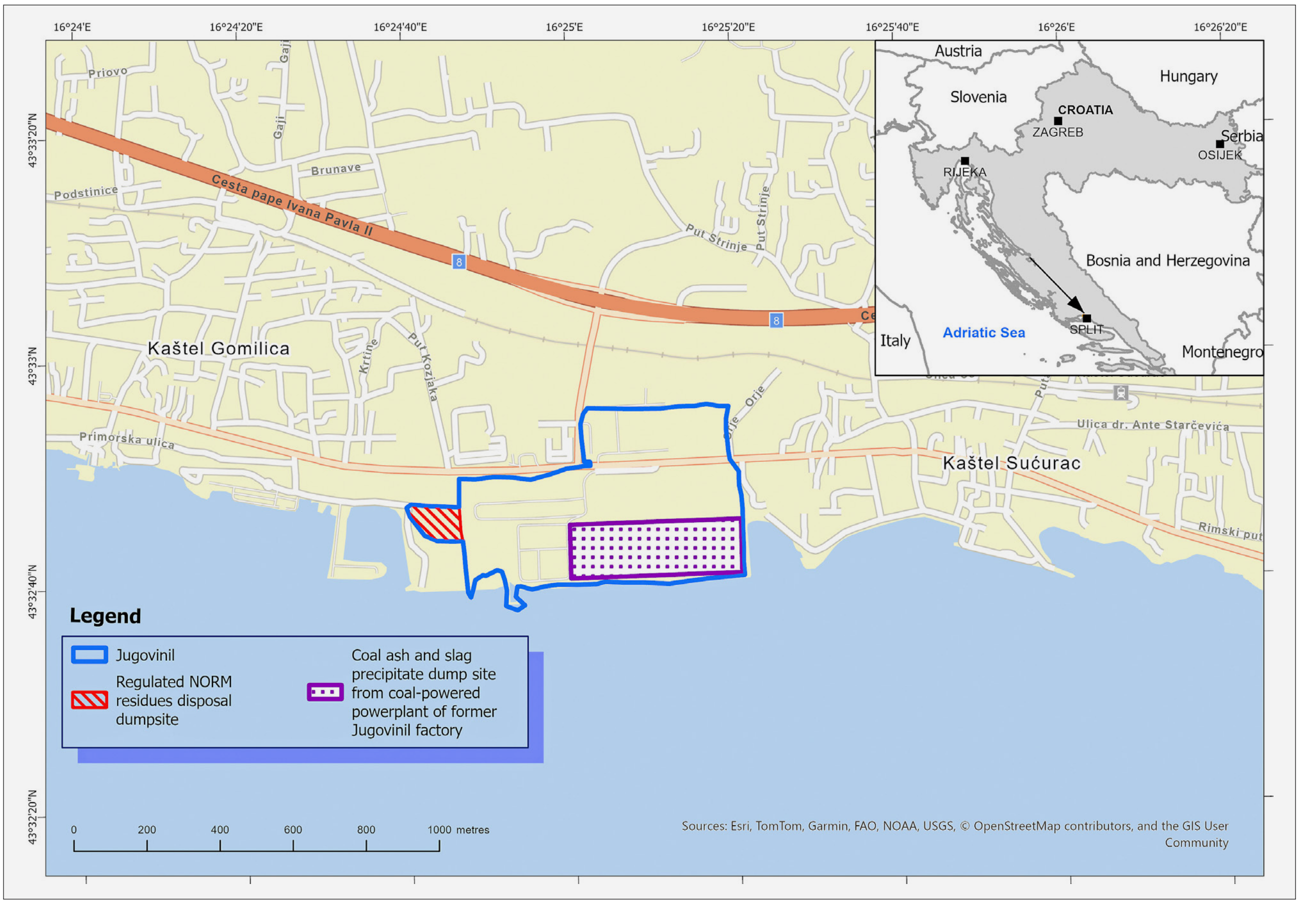

Figure 1. Three distinguished areas of interest in the Kaštela Bay: the site of the ex-Jugovinil factory (blue line), regulated NORM residues disposal site (red pattern) and the location of coal ash and slag solid precipitate dump from the powerplant of the Jugovinil factory.

- *Former industrial areas and sites* – which include any type of industry, from food processing to chemical processing plants, and old powerplants.
- *Mining sites, including oilfields, and mineral processing sites* – which contain waste rock, tailings, and, in rare cases, remaining mine water, or more commonly mine water precipitate. These materials, in turn, usually contain NORM (naturally occurring radioactive materials) residues, sometimes other heavy metals, chemicals used in mineral processing, etc. The reason for distinguishing mining sites and mineral processing sites from other industrial sites is in the size and the amounts of materials.

The Republic of Croatia (RC) has several identified brownfield sites, some of which contain NORM residues (**Veinović et al., 2020**), and three of which are mentioned in the National Program on the Implementation of Strategy for radioactive waste (RW), disused sealed radioactive sources (DSRS) and spent nuclear fuel (SNF) Management in Republic of Croatia (**Official Gazette, 2014 & 2018**):

- Coal ash and slag disposal sites of thermal power plants Plomin I and II.
- Phosphogypsum disposal site of Petrokemija d.d., Fertiliser Factory, Kutina.
- Coal ash and slag solid precipitate dump site in Kaštela Bay from powerplant of the ex-Jugovinil factory for the production of plastics and chemical products in Kaštela Bay.

This paper deals with the brownfield site of the former factory of plastics and chemical products, Jugovinil, in the city of Kaštela, Croatia, located in Kaštela Bay on the very coast of the Adriatic Sea, which is not yet regulated, remediated nor under institutional control. The main reason for taking interest in this brownfield site are planned activities related to the reclamation of this site, urbanisation and adapting for tourism purposes or, alternatively, as a small "Green Energy" production site. Original research done on site (**Prlić, 2011a-d**) was performed to assess the situation, define the borders of the brownfield area, identify and categorise contaminants, and assess the existing and potential impact on the environment. Special attention was given to the assessment of the contaminants' impact on the biota which will provide for a correct risk assessment (**Skoko et al., 2023; Getaldić et al., 2023**) and, thusly, help in the management of the location, starting with the development of remediation protocols and methods (**EPA, 1989; IAEA, 2004a**). Before any urban repurposing of the site, it is necessary to build up a regulatory matrix for construction purposes and design.

Figure 1 shows the location of this brownfield site on Croatian coast, placing it mostly in Kaštel Sućurac, and partly in the neighbouring Kaštel Gomilica, two towns which are part of the city of Kaštela.

As shown in **Figure 1**, there are three primary recognisable areas of interest (**Prlić, 2011c**):

- the site of the former factory of plastics and chemical products, Jugovinil (area marked with blue border, **Figure 1**).
- regulated disposal site (the area marked with a red pattern, **Figure 1**), located in Kaštel Gomilica and containing 30,000 m^3 of NORM residues, namely coal ash and slag transported from other coal-powered thermal power plants in the former Socialist Federal Republic of Yugoslavia (SFRY). Although the material contains only coal ash and slag, according to the Decision of sanitary inspectorate (**SFRY, 1974**), it is defined as "uranium ore tailings from coal", due to a high percentage of uranium in certain coals mined and used in ex-SFRY. The disposal site was properly designed and closed for any other activity in 1973, however, this location was in 2014, unadvisedly by regulators, lent for use to a private enterprise under the concession contract for 30 years and under the condition it was not to be disturbed.
- Coal ash and slag precipitate dump site in Kaštel Sućurac (the area marked with a purple pattern, **Figure 1**), containing 180,000 m^3 of coal ash and slag precipitate dump site from the powerplant of the former Jugovinil factory, deposited utilising hydro transport of the material which sedimented in the specially constructed and protected area created by construction of the embankment in the sea and filling the thusly gained terrain with rock and soil. The outer wall of the dump site (embankment) now forms the breakwater barrier of the bay. The dump site was constructed in the 1980's and was used until the 2000's.

It must be noted that there are several smaller polluted zones with deposits of ash and slag along with the abovementioned sites, created mostly during maintenance of the factory site throughout its operation.

Since the Jugovinil factory, along with its powerplant, was decommissioned, and most of the structures demolished (**Ester et al., 2005**), during the last three decades, part of the wider location, bordering the regulated NORM residues disposal site in Kaštel Gomilica, was repurposed as a marina, berth and anchorage, with the supporting facilities. That information is important because of possible further contamination of the entire location in case of damage to the disposal site's protective layers.

The entire precipitate dump site (the area marked with a purple pattern, **Figure 1**) has a rich biota and is covered with wild vegetation in an advanced stage of growth (Lugistrum vulgaris, Tamaricaceae gallica, Weissia dalmatica, Spartium junceum, Satureja subspicata, Myrto-Pistacietum lentisci, Vitici-Tamaricetum dalmaticae, etc.), and there are many examples of autochthonous fauna (**Prlić, 2011a-d; Skoko et al., 2023**). This biodiversity on such a site is another topic for planned detailed scientific research.

This brownfield site is an example of the multiple stressors environment for biota (**Segner et al., 2014; Megharaj & Naidu, 2017**), since it contains not only naturally occurring radionuclides in the form of NORM residues, but also a basic pH factor, due to the basicity of coal ash and slag mixture with water (**Popović & Đorđević, 2009**), and a certain amount of heavy metals (nonradioactive isotopes) (**Dragović et al., 2008**).

From several naturally occurring isotopes identified in samples of soil taken from the location (**Prlić, 2011a-d; Radas, 2024**), three isotopes from the 4n decay chain of ^{232}Th, also known as the "thorium series", were analysed to be presented in this paper, and data was presented in concentration maps in this paper. The mentioned isotopes are: ^{228}Ac, ^{212}Bi and ^{208}Tl (see **Figure 2**).

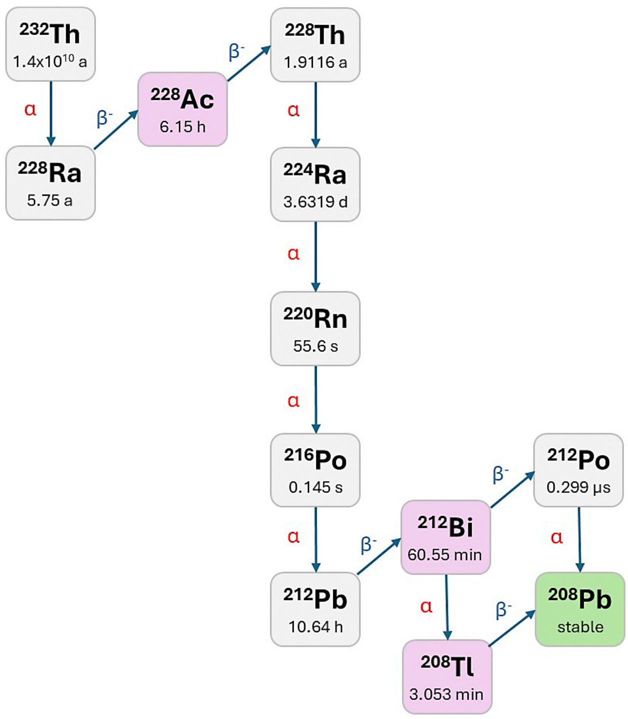

Figure 2. The 4n decay chain of ^{232}Th, also known as the "thorium series".

As it is applied in this study, a selection of isotopes from the same chain helps their distribution analyses, and thusly measurements can be examined for possible sampling errors. Combined analyses of measured concentrations and maps resulting from spatial representation of radionuclide concentrations allows for corrections in final reports, since "the perfect map" could be obtained by more dense and frequent sampling and laboratory analy-

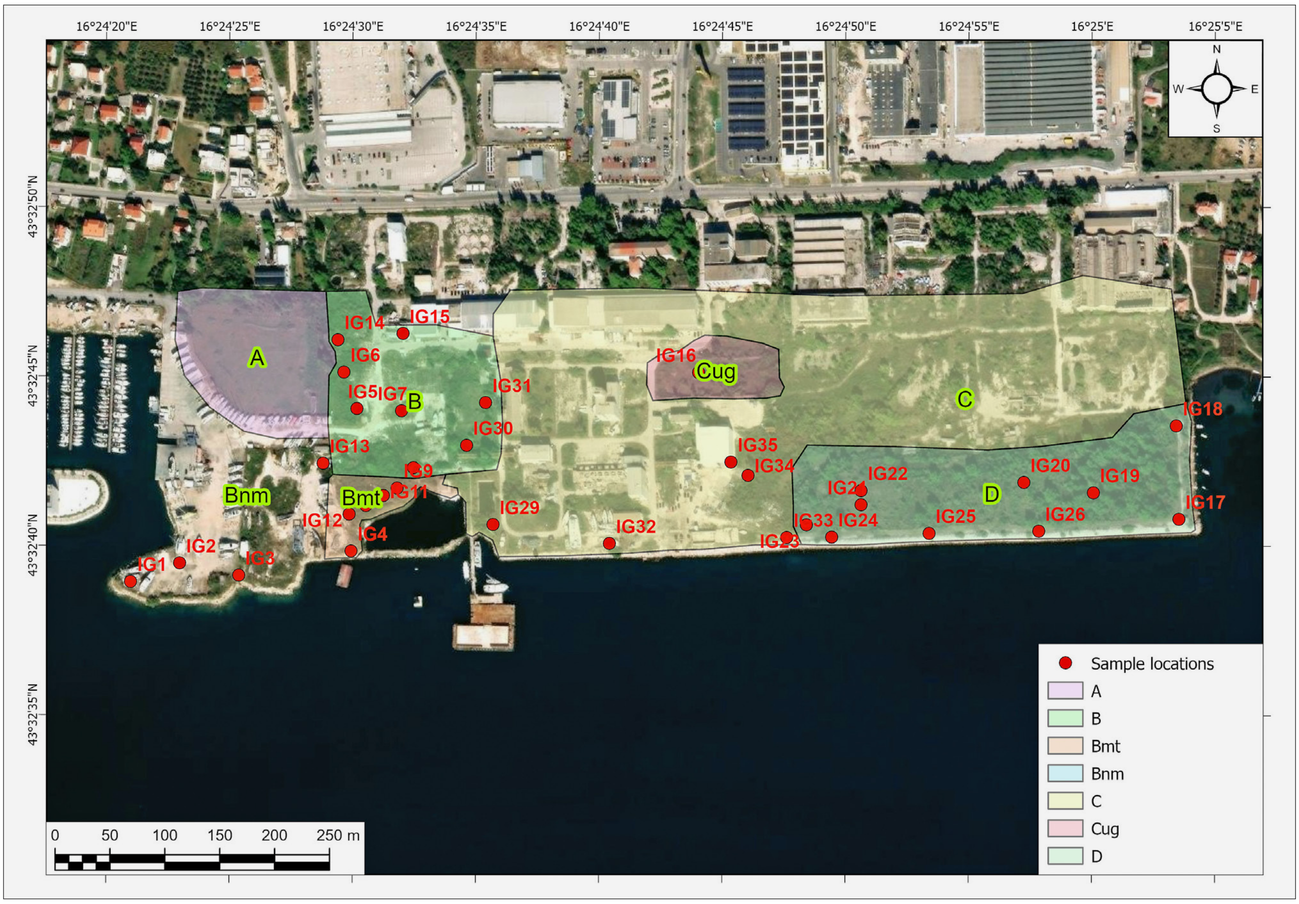

Figure 3. Specific areas of the site and sampling locations (IG1-IG35)

sis. That being an expensive approach, analysing maps and relationships between radionuclides, a better approximation of results can be obtained in areas where samples were not collected but mathematically interpolated, and possible errors can be avoided. Interpolation gives an area ("cloud") of probable concentrations of the certain element, and it must be said that there is a probability that the presented concentration on a certain micro-location may differ from the actual one. The results of probable concentrations can be shown in denser iso-lines and smaller areas of the same colour representing certain element concentrations on the map, however, the best representation is applying WEB-GIS instead of paper maps, since in WEB-GIS not only are probable concentrations shown in graduated colours, but also the measured data can be presented as a floating table on the map, if the user is hovering with a cursor over the sampling coordinates indicated on the map with a marker.

2. Methods

Complete research done on the entire location of the ex-Jugovinil factory (**Prlić, 2011a-d**) includes:

- Detailed surveying of the location.
- Soil sampling at multiple locations on the surface (composite sample taken from a 15 cm depth and 1 square m area) and from several exploratory boreholes (disturbed core samples, as the term is used in soil mechanics).
- Sampling of geological materials from the seabed in the immediate vicinity of the location alongside the constructed embankment and shoreline.
- Sampling biota from the location and from the sea (benthic samples).
- Sampling of water from ash and slag precipitate in order to detect a potential breakthrough of sea water through the embankment into the precipitate (which would be an indicator that naturally occurring radionuclides from coal and ash are migrating with the freshwater into the sea).
- Sampling the benthos at the seabed to detect possible traces of naturally occurring radionuclides from coal and ash which ended up in the sea (due to a deliberate or incidental spillover from precipitate dumpsite).
- Measurements of the concentration of heavy metals from samples.
- Measurements of radionuclide concentrations from samples.
- Measurements of the ambient dose rate ([H*(10)/t]; trace method) on the surface of the location (including and excluding local natural background activity).

- Measurements of the ambient dose rate ([H*(10)/t] trace method) on the surface of the seabed (special well drilling probe trace method).
- VR gamma spectrometry measurements of radon concentration from soil material samples.
- Determination of the hydrogeological and seismic properties of the location.
- Determination of the basic geological properties of the location.
- Filming the entire location with a drone (recent investigative works), in order to detect and map flora and fauna changes through time, and with seasons.
- Special research on endemic species which were found at the precipitate dump D (**Skoko et al., 2023**).

On-site research began with surveying to acquire data on the spread of different materials, as well as for defining sites for surface and borehole sampling of materials. Sampling locations (IG1-IG34) are shown in **Figure 3**.

It has to be noted that for the detailed research related to contaminant dispersion, the determination of the hydrogeological properties of the location are crucial. In the initial research, the results show that radionuclides from dumped materials are not further redistributed due to hydrogeological conditions, including possible contamination of the sea bottom sediments. However, if further research is to be done, hydrogeological properties of the location will be performed again, which will, in turn, show whether there was any dispersion of radionuclides or other contaminants on the location or in its vicinity.

Seven distinguished areas of interest for the detailed research are identified on site (see **Figure 3**):

- A – location of the regulated NORM residues disposal site: coal ash and slag transported from other coal-powered thermal power plants in the SFRY.
- B – area partially covered with coal ash and slag and construction waste material (in 1970's and 1980's) in order to level the location and prepare it for the construction of new industrial facility – reservoirs for chemicals, as well as a part of site backfilled (end of 1990's) in order to create a site for the service zone of the existing marina.
- Bnm – area given in concession, created by dumping soil material into the sea (material gained by excavation in other locations, e.g. excavation for the construction of a shopping centre in the city of Split, Croatia; excavation for the construction of an expressway around Split, etc.) in order to construct anchorage and dry dock.
- Bmt – area filled with ash and slag from the powerplant (99 % of the bulk material), plastic and construction waste, zone of deliberate sea backfilling to save space in the precipitate dump site ("D").
- C – area created by cleaning/remediation of coal ash and slag gathered in 1971-1973 and transferred to location "A" and then backfilled and levelled (mostly) with soil/rock material and some construction waste in order to prepare terrain for the construction of new factory facility (1974).
- Cug – coal storage for the thermal power plant of the former Jugovinil factory (containing approximately 4,000 t of coal in 2010), in existence since the start of the Jugovinil factory operations (1947).
- D – coal ash and slag precipitate dump site from the powerplant of the former Jugovinil factory.

2.1. Sampling and measurements

As stated before, in this paper only the results of the concentrations of three thorium series radionuclides are shown, throughout the entire area of interest. Other measurements and their results are planned to be discussed and published in future publications, due to need of the additional data analysis and type of pollutants.

Surveying the location, among other things, provided a precise line of the water line (contact between the sea and the land), and depth of the sea – depth relief of the Kaštela Bay (**Prlić, 2011c**). This georeferenced situational plan is the basis for all cartographic representations in this paper, and it is aligned with the digital orthophoto imagery.

Soil material on site considered in this research varies from hard rock (limestone), over soil (Terra Rossa) to weathered ash and slag, different types of waste (plastic, construction, etc.) and in certain places (natural depressions in the ground) humus developed over time. Certain locations were completely covered with dust (particles ≤ 400 μm) and pieces of concrete created by the demolition of factory buildings.

The reason for the research of the seabed and sea flora and fauna was the construction of the precipitator/settlement pond, in which the ash and slag were delivered using hydro-transport from the powerplant, employing water from the nearby Jadro River. Excess water used for the hydro-transport overflowed into the sea and, inevitably, some of the ash and slag material ended up in the sea as well. In order to properly explore the site, it was necessary to determine which materials, if any, ended up in the sea and in what quantity. This research is more complicated due to influencing factors, such as: marine sediments precipitated since ash and slag disposal stopped and the transport of radionuclides and radionuclide containing materials due to the influence of sea currents.

While correlations between the concentrations of different radionuclides are determined with their place in a certain element series and half-lives of isotopes and their progeny (e.g. ^{228}Ac, ^{212}Bi and ^{208}Tl in the 4n decay chain of ^{232}Th, see **Figure 2**), there is an issue of the origin that has to be considered, since the concentrations of radionuclides can be measured in site-specific soil/rock materials (background radiation) or in anthropogenically in-

Table 1. Concentrations of respective radionuclides related to sample IDs and sampling areas, along with standardised concentration values

ID	Zone	^{228}Ac (Bq/kg)	^{212}Bi (Bq/kg)	^{208}Tl (Bq/kg)	^{228}Ac_st	^{212}Bi_st	^{208}Tl_st
IG1	Bnm	22.81313	10.247273	27.221613	0.162017	0.364762	0.179245
IG2	Bnm	17.930194	-6.596957	18.773526	0.101768	0	0.09434
IG3	Bnm	28.771706	11.361426	48.185385	0.235539	0.388889	0.389937
IG4	Bmt	15.286579	6.596957	23.154016	0.069149	0.285714	0.138365
IG5	B	29.65662	32.404723	38.798621	0.246457	0.844582	0.295597
IG6	B	59.077224	29.686306	40.05019	0.60947	0.785714	0.308176
IG7	B	25.943027	27.111736	16.896174	0.200636	0.729962	0.075472
IG8	B	9.68232	21.467704	48.811169	0	0.60774	0.396226
IG9	Bmt	69.653047	12.827416	102.628611	0.739962	0.420635	0.937107
IG10	Bmt	31.988	12.827416	73.216753	0.275224	0.420635	0.641509
IG11	Bmt	33.393639	31.39897	108.886453	0.292567	0.822802	1
IG12	Bmt	45.506983	2.565483	42.553327	0.442031	0.198413	0.333333
IG13	Bmt	11.386946	5.130966	26.282937	0.021033	0.253968	0.169811
IG14	B	27.968783	35.865456	45.682248	0.225632	0.919524	0.36478
IG15	B	48.373339	16.99318	20.650879	0.477398	0.510845	0.113208
IG16	Cug	42.631452	24.031985	23.869753	0.40655	0.66327	0.145558
IG17	D	29.82431	15.37091	14.869528	0.248526	0.475714	0.055103
IG18	D	23.953972	10.628431	17.976383	0.176094	0.373016	0.086328
IG19	D	49.688508	36.068201	69.462048	0.493625	0.923914	0.603774
IG20	D	90.727975	36.947068	46.308032	1	0.942946	0.371069
IG21	D	59.9596	35.125882	48.185385	0.620358	0.903508	0.389937
IG22	D	40.981878	39.581741	46.933816	0.386197	1	0.377358
IG23	D	61.94358	22.356354	26.282937	0.644837	0.626984	0.169811
IG24	D	35.80885	26.125523	18.773526	0.322368	0.708606	0.09434
IG25	D	49.580944	23.788	28.786074	0.492298	0.657986	0.194969
IG26	D	64.505594	23.479452	20.650879	0.676449	0.651305	0.113208
IG29	C	13.83632	12.076527	15.152783	0.051255	0.404374	0.05795
IG30	B	36.204943	16.202361	22.016483	0.327255	0.493719	0.126932
IG31	B	22.313572	18.155001	15.430839	0.155854	0.536004	0.060745
IG32	C	13.968872	13.118466	10.638332	0.052891	0.426938	0.012579
IG33	C	27.982058	14.659904	18.773526	0.225795	0.460317	0.09434
IG34	C	33.696419	20.523866	18.147742	0.296303	0.587302	0.08805
IG35	C	17.916508	10.93576	9.386763	0.101599	0.379671	0

troduced materials. Therefore, isotopes have to be considered as a natural occurrence in different soils, as well as those found in materials disposed of on-site, e.g. NORM residues in the form of coal ash and slag. To assess differences in concentrations, it's essential to consider the specific characteristics of each radionuclide, the complexity of environmental systems, and the context of the study area when interpreting results of the concentration analysis (**Tokonami & Ishikawa, 2007; IAEA, 2013; Lauer et al., 2015; IAEA, 2022 & 2024**).

Samples were collected in accordance with the IAEA sampling protocol (**IAEA, 2004a; Prlić, 2011d**) which considered locations demonstrating the most relevant characteristics of the site and its environment. It has to be noted that sampling from the area "A" (see **Figure 3**) was not performed due to its status, as the regulated disposal site, with proper protective layers which prohibits transfer and redistribution of radionuclides. Only surface measurement of ionising radiation dose rates was done (as for this whole brownfield site), and the results show significantly lower dose rates than in other areas, which will be presented in another publication. The reasons for this are recent dose rate measurements which will, after data processing and interpretation, be compared to those measured 15 years ago, in order to assess possible anthropogenic changes through time.

From a representative set of 40 samples of "soil" acquired on the location (see **Table 1**) concentrations of ^{228}Ac, ^{212}Bi and ^{208}Tl were determined in the Institute for Medical Research and Occupational Health laboratories. Several samples were outside of the area of interest and were not analysed considering radioisotopes or, as in the case of and IG27 and IG28 sampling locations, results of isotope concentrations were excluded due to the extensive distance from other sampling points. On location "A" (see **Figure 3**) no samples were taken, since this regulated NORM residues disposal site is not to be disturbed, sampling would affect the landfill protective layers. Dose rates were measured on location "A", as well as on all other considered locations on this site, and the results are to be published in future research papers.

Each dataset of three radionuclide concentrations (columns 3-5 in **Table 1**) has different attributes in terms of the absolute value range, but all are in the same units of measurement, while data in columns 6-8 is standardised, and **Table 1** shows relative values with the suffix "st". There are four standardisation methods: Z-Score, Minimum-maximum, Absolute maximum, and Robust standardisation. The Minimum-maximum method, used here (see **Equation 1**), preserves the relationships among the original data values while converting the values to a scale between user-specified minimum and maximum values. Min-Max standardisation is essentially the same as the normalisation of the data. This method transforms the values into a new range, typically from 0 to 1, which is especially useful when we have values in different ranges (e.g., 2-10, 400-500, 15000-16000 µg/g) (**García et al., 2015; Koduru, 2022**).

$$x' = a + \frac{(x - \min(x))(b - a)}{\max(x) - \min(x)} \tag{1}$$

where:

x' – standardised value,
x – original value,
min(x) – minimum of the data,
max(x) – maximum of the data,
a – user-specified minimum,
b – user-specified maximum.

This approach (Minimum-maximum method) is prone to influence by outliers, or extreme values, in the data, but data are already checked before interpolation. In this way, data could be combined in a cumulative dataset of values for the resulting map of concentrations. The same principle would be applied in case of representing several isotope concentrations, or a combination of different pollutants, when considering multiple stressors in the environment for biota.

2.2. GIS technology

GIS (Geographic Information System) technology is often used in pollution management and monitoring because it enables the analysis and mapping of various collected data types. The GIS software allows for the integration of different data sources as input data, such as air, water, or soil quality measurements, as in this article. Also, different types of background maps (base maps) are used depending on the purpose of the analysis, available data and required level of detail: satellite imagery, aerial imagery (orthophoto), topographic maps, and more.

Demers (**1997**) is the first who gave a comprehensive introduction to GIS principles and applications, including environmental monitoring and the integration of various data sources. **Lillesand et al.** (**2004**) described the use of remote sensing and GIS in environmental analysis, covering topics such as satellite imagery, aerial photography, and their applications in monitoring environmental pollution. The "Big Book of GIS" (**Longley et al., 2005**) describes the scientific GIS approach but also its practical applications, including environmental management and the use of various background maps for many analytical purposes.

As mentioned in the abstract, one of the main tools for BFS management is the utilisation of GIS technology at two levels:

- Representation of all BFS in the country.
- Representation of material/pollutant distribution (surface, amount and concentrations, etc.) for the respective sites.

Concerning the state level, i.e. representation of all BFS in the country, an information system is already designed. The Spatial Planning Information System (ISPU) of the Ministry of Physical Planning, Construction, and State Assets of the Republic of Croatia is the national system for entering, verifying, publicly publishing, and exchanging spatial data for the purpose of creating, adopting, implementing, and monitoring spatial plans, as well as for the ongoing monitoring of spatial conditions and the area of spatial planning. ISPU ensures transparency and accessibility of the spatial planning system and allows for simple oversight and control of all processes occurring within it, which is crucial for the effective management of brownfield sites (**Berc, 2023**).

Matković & Jakovčić (**2019**) depict the concept of GIS application in Croatia. This paper analyses the issues surrounding abandoned, previously used spaces and their repurposing and sustainable use. The authors explain the development of the concept of brownfield spaces and the related concept of regeneration, highlight the inconsistency in the use of the term brownfield, and provide a description of potential brownfield categorisations based on various criteria. The factors contributing to the success of brownfield regeneration are specifically discussed. The first level of utilisation is important since the number of BFSs, amount of space occupied by them, their position relative to urban areas, agricultural areas or aquifers, etc., can help future spatial planning, protection of resources and other actions on the level of the whole country. GIS technology applied on specific sites will readily include several layers of data, starting from the topographical characteristics of the site, specific locations of constructions on the location, up to concentrations of different materials, their cumulative concentrations, other measurable data and data calculated from it (e.g. risk intensity shown in zones). GIS can be used in the redevelopment of brownfield sites, can define methodology for characterising inventory of brownfield sites, providing access to governments and private investors and be integrated with geostatistics in the brownfield remediation process, with the aim of optimising urban planning (**Boott et al., 2001; Schrooten & Van Alphen, 2008; Ippolito et al., 2023**).

For this research, concentrations of respective radionuclides (see **Table 1**) were used as input data for radionuclide concentration maps to study the spatial distribution of radionuclides in soils.

A powerful GIS engine in ArcGIS Pro software was utilised for digitising, vector-based analysis, modelling and data standardisation. Gridding was performed by GIS geostatistical extension Geostatistical Analyst, using a 1×1 m² grid size, incorporating all 33 available input points. These points are displayed as a layer with sampling locations (IG1-IG35) in **Figure 3**, also with relevant zones of the location. The interpolation was performed using the geostatistical method Empirical Bayesian Kriging, which was instrumental in designing radionuclide concentration maps. Finally, further raster-based analysis and modelling is performed with the tool Raster Calculator, using standardised values of radionuclides, to obtain the resulting map of combined concentrations. Empirical Bayesian Kriging (EBK) is a more recent geostatistical method, used in GIS software to estimate values at locations where data have not been collected, based on known data points (**Krivoruchko & Gribov, 2019; Gribov & Krivoruchko, 2020**). Unlike ordinary kriging, it takes into account spatial variability from the entire dataset, not just from neighbouring points. The dataset is divided into subsets to better understand spatial variability within each subset, which is especially important in complex datasets where spatial patterns are not uniform. The variogram parameters are then estimated. A variogram describes how data are related over different distances, separately for each subset. By processing each subset individually, the specific characteristics of each are more accurately captured. This approach allows for more flexible and adaptive modelling of spatial variability compared to ordinary kriging, which can only assume a single variogram for the entire dataset. EBK is particularly useful in environmental studies, such as mapping pollution levels or predicting soil contamination, where precision is crucial for analysis and remediation planning (**Radas, 2024**).

3. Results

Interpolation maps of ^{228}Ac, ^{212}Bi and ^{208}Tl concentrations are given in **Figures 4-6**, respectively, and the (cumulative) map of combined standardised concentrations of measured radionuclides is given in **Figure 7**. Radionuclide concentration distribution is, as was expected, aligned closely with the type of material found on the abovementioned seven distinguished areas of interest.

The Normal QQ Plot (see **Figures 4-6**) displays a scatterplot of the standardized errors versus the equivalent quantile of a standard normal distribution. If the cross-validation errors are normally distributed and the standard errors are estimated accurately, the points in the plot should all fall close to the reference line. Reviewing this plot is most important when using the quantile or probability output types because they require normally distributed errors (**Macenić et al., 2020**).

It has to be noted that no samples were taken from location "A" (see **Figure 3**), since this regulated NORM residues disposal site is not to be disturbed, sampling would affect the landfill protective layers. Therefore, the resulting areas showing probable concentrations are interpolated as is, and the only way to avoid this "error" would be to place "virtual sampling points" around the location "A" with concentration values of 0.00 Bq/kg. The authors decided against that and therefore this explanation.

Zone "D" consists of *coal ash and slag precipitate dump site from the powerplant of the former Jugovinil factory* and therefore shows the most significant concentrations of radionuclides. Zone "B" is an area predominantly backfilled with rock/soil and construction waste material and a small amount of coal ash and slag originated on-site in a local powerplant. These materials are not covered with the protective materials (as e.g. area "A" is), and therefore radionuclides from coal ash and slag are exposed to the atmosphere, rain, wind, etc. which can induce their redistribution. Area "Bmt" is also partially filled with ash and slag from the powerplant (99 % of the bulk material), plastic and construction waste. Since it is also open to the influence of atmospheric effects, which results in radionuclide redistribution, the results are not unexpected.

Certain "shading" of zones "A" and "Bnm" is due to mathematical approximation and automatic adjusting of data representation to measurements at specific locations, and not due to elevated concentrations. Therefore, since sampling at zone "A" is out of question, it being covered with protective layers, surface measurements of dose-rates and application of handheld radionuclide identification devices (RIDs) will give additional data needed for more precise assessment. RIDs are instruments that identify radionuclides present in a sample of material by identifying characteristic gamma ray emission patterns, and combined with dose-rate measurements can give an approximation of contamination of a

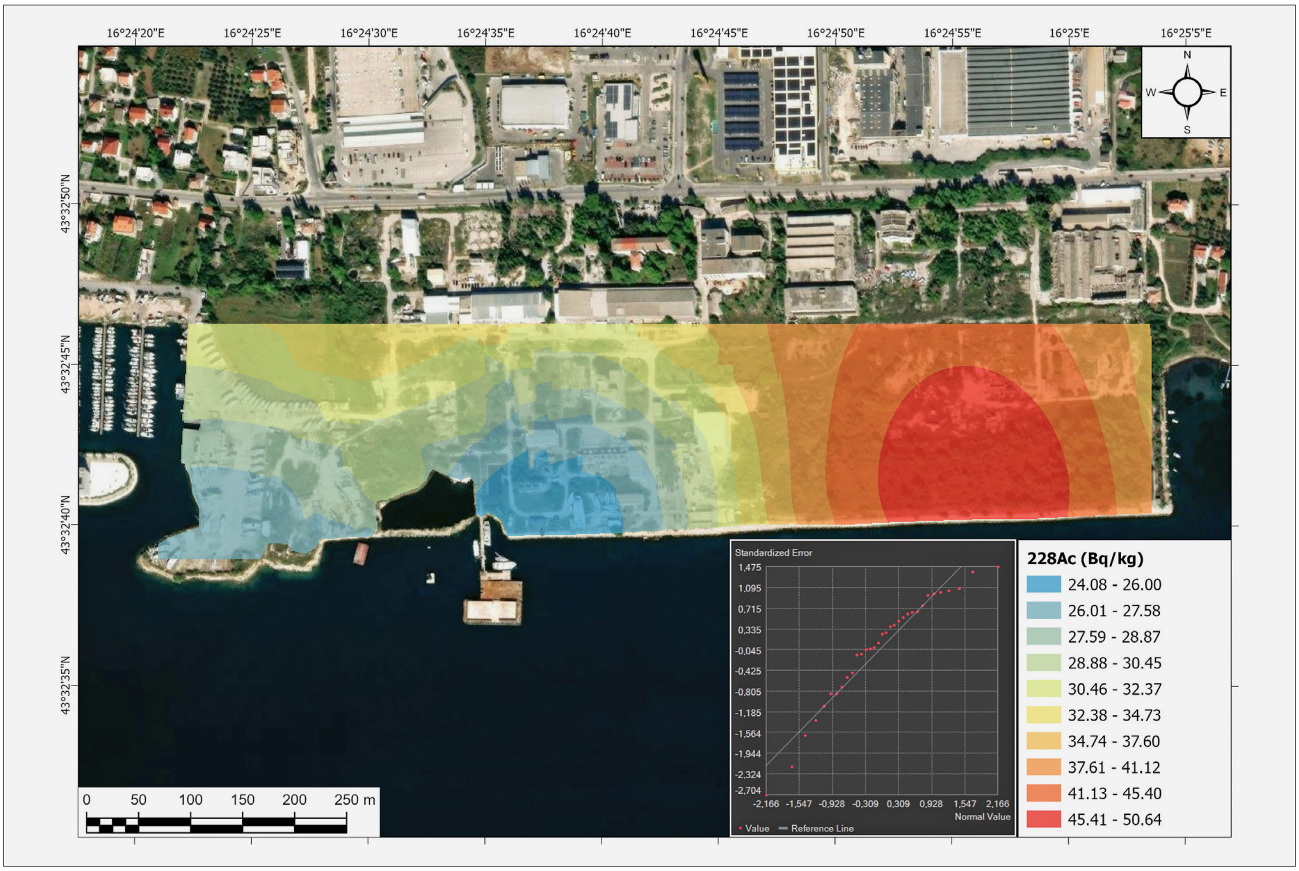

Figure 4. Interpolation map of ^{228}Ac concentration

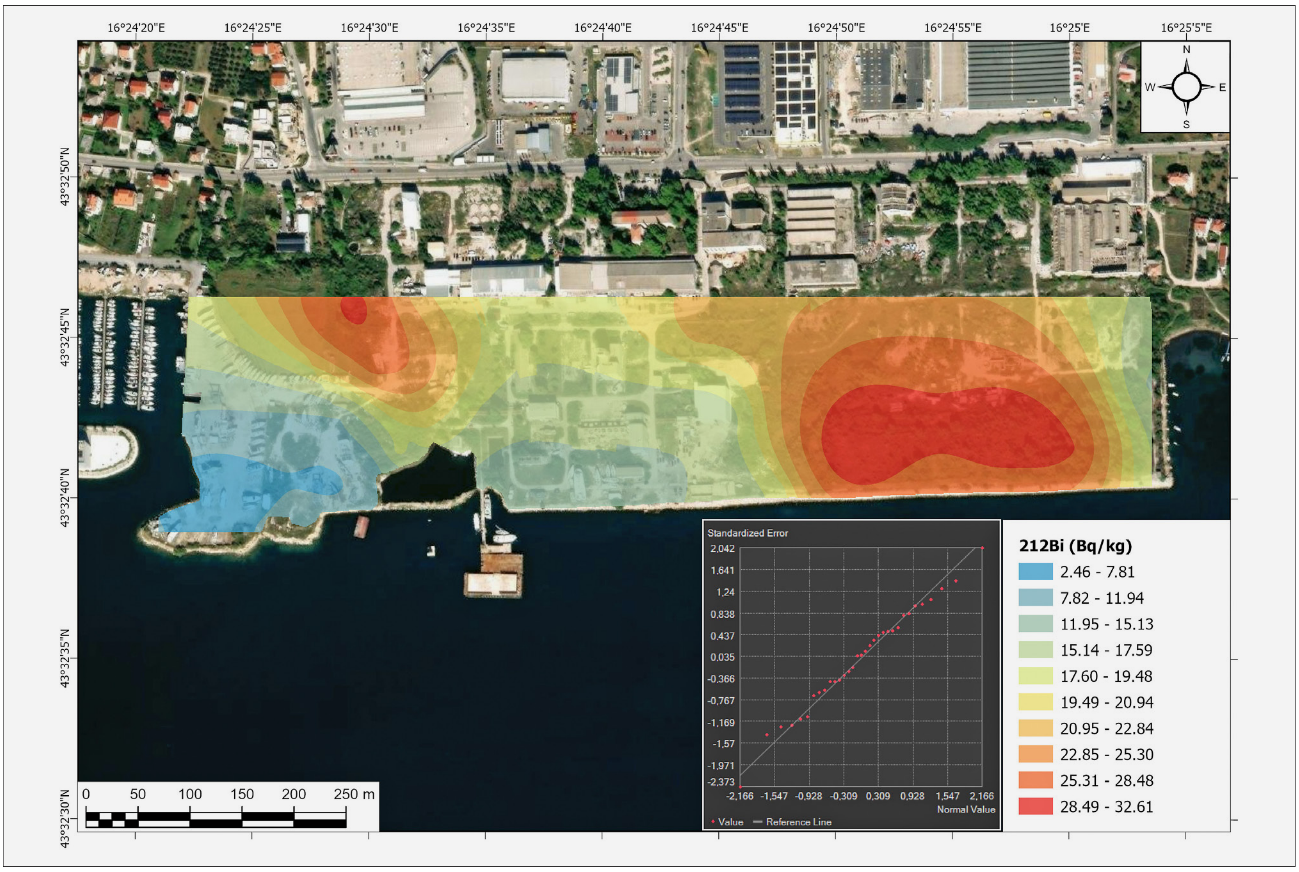

Figure 5. Interpolation map of ^{212}Bi concentration

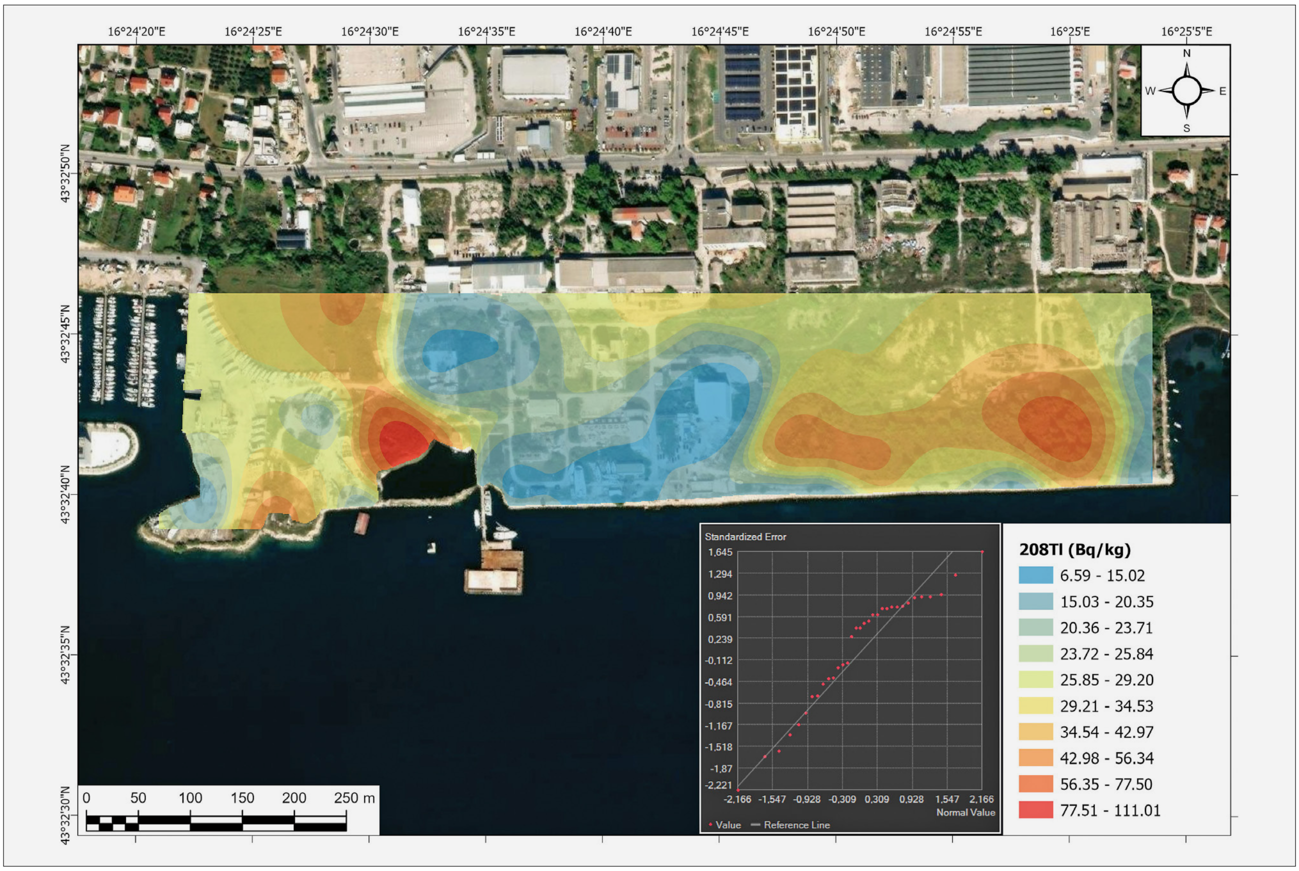

Figure 6. Interpolation map of ^{208}Tl concentration

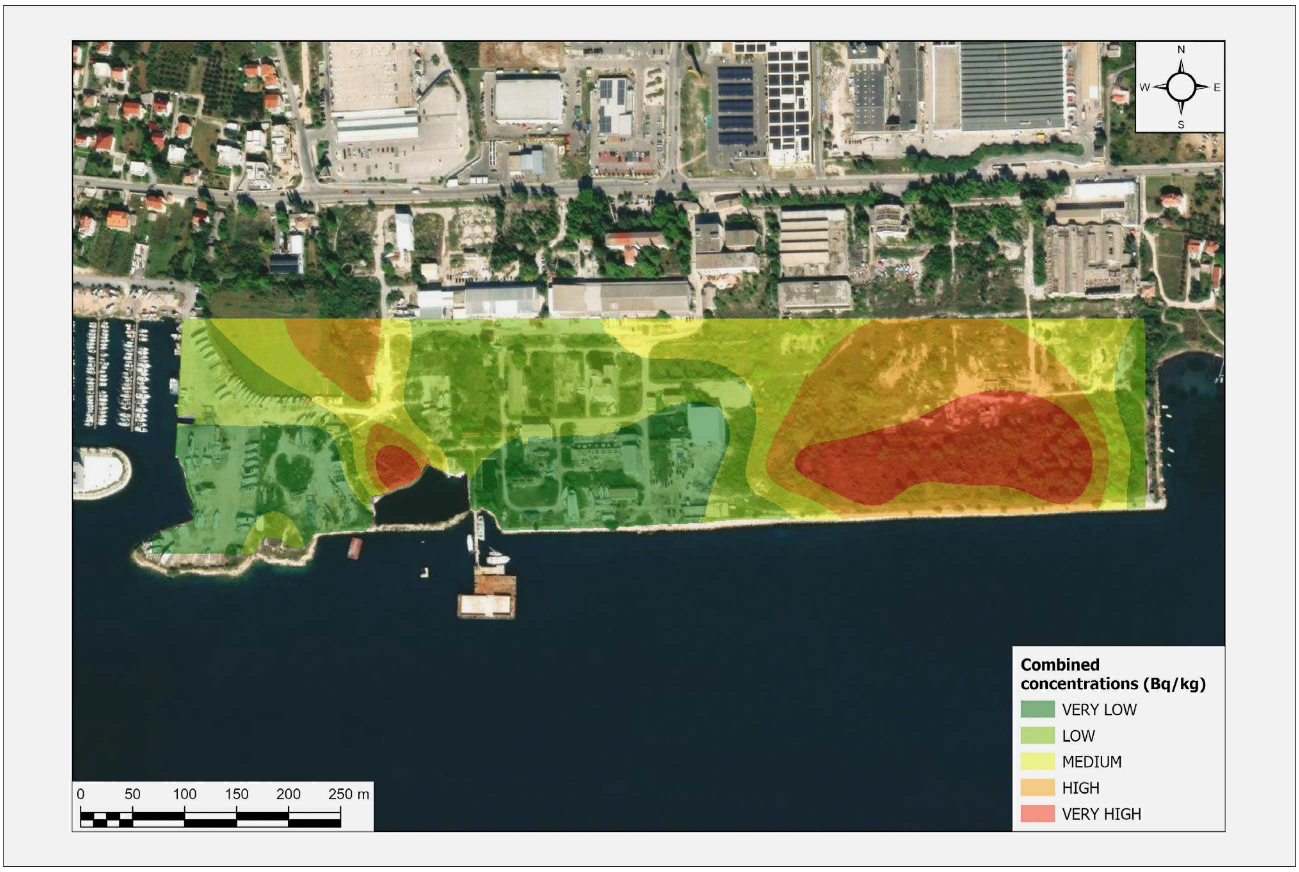

Figure 7. Combined map with standardised concentrations of ^{228}Ac, ^{212}Bi and ^{208}Tl

certain location. These measurements are partially done and partially planned for 2025, and these results are intended to be published upon research completion.

4. Discussion

This brownfield site is an example of the multiple stressor's environment for biota, but, when it is mentioned in regulatory documents, scientific papers, etc., the emphasis is readily on radionuclides and their impact on biota, or risk estimation related to radionuclides. Guided by that, this paper, initially being published as part of a planned series, deals with the analysis of measured data and its representation in the form of maps. It shows potential zones of high interest during remediation, helps with the decision-making related to remediation methods and technology, but also indicates which additional measurements and research must be done in order to perform qualitative assessment before the remediation starts.

The contour lines connect areas of equal concentration, making it easier to identify hotspots of contamination and patterns of spread (see **Figures 4-7**). This spatial representation is crucial for several reasons: visualisation of contamination distribution, risk assessment and decision-making, compliance and reporting, and site remediation and reuse/development. The contour maps, particularly when representing the concentration of contaminants, are an essential tool for both understanding and managing contaminated brownfield sites.

Specifically in this study, GIS maps are useful for identifying the exact zones with higher concentrations of radionuclides, tracking changes in measured concentrations over time (regular measurements will become mandatory when the whole area goes under regulative control), and modelling the impacts of potential pollutant spread. It must be noted that concentrations of radionuclides are measurable to a depth of several centimetres (or more, depending on the deposited material) and, hence, contour mapping shows concentrations of the composite samples (average bulk concentrations by depth), and a specific representation of the results by depth (in layers) is also possible. All this facilitates better risk assessment, targeted interventions, and informed decision-making, because GIS enhances effective communication with the public through clear, data-driven visualisations. This approach can initiate positive public opinion and interest about this and other brownfield sites in Croatia, which is one of critical premises in NORM residues and brownfield sites management in general. Since the site in Kaštela Bay is in the media readily considered a "polluted site with a lot of radionuclides, and as such problematic for any kind of remediation", publishing results in the form of maps or by utilisation of WEB-GIS approach for dissemination of research on this site, will help stakeholder engagement, improve communication with stakeholders and keep them well informed. Open and clear dissemination of the research results will improve public perception of environmental issues and help in the proper management of this and potentially other brownfield sites.

Another significant aspect of data representation and dissemination has to be considered here – its impact on tourism. Since the Croatian economy heavily relies on tourism (**CBS, 2003 & 2024**), brownfield sites can have a noteworthy impact. Leaving a brownfield site located on the very Adriatic coast "as is", reduces potential tourist capacity and resources due to lost areas, and in the case of Kaštela Bay, of significant size. This brownfield site is located between important tourist centres, and apart from the loss of resources, the impact of information that tourists are situated near the NORM residues dumpsite, can affect the popularity of the area.

5. Conclusions

The use of GIS for mapping point data and generating contour maps is fundamental in the analysis and management of all brownfield sites. GIS professionals can create continuous surfaces that reveal the probable concentrations of certain contaminants, support environmental decision-making, and aid in the planning of remediation strategies. Since there is a probability that a presented concentration on a certain micro-location may differ from the actual one, and continuous surfaces are in fact showing probable concentrations, the best representation is applying WEB-GIS so that the actual measured data can be presented as a floating table on a map if the user hovers with a cursor over the sampling coordinates indicated on the map with a marker. Contour maps are not only essential for visualising contamination, but also for ensuring that safe, sustainable redevelopment options are pursued for brownfield sites.

In this study, three separate interpolation maps were generated for each radionuclide, highlighting specific zones of contamination. Also, a summarised map was created. This map integrates normalised concentration values, providing a comprehensive overview of total contamination. The combined map is very efficient in the interpretation of pollution levels by aggregating multiple sources of contamination into a single spatial dataset.

The methodology presented in this study will be applied for the rest of the contaminants on this site, other radionuclides and all heavy metals, creating a complete state of the location, and can also be applied to other contaminated sites, enhancing environmental management strategies and supporting informed administrative processes, maybe even the aforementioned ISPU.

Moreover, incorporating time-series data enables more precise monitoring. By comparing data before and after an intervention, it's easy to find out whether the pollution levels are decreasing as expected, and identify any potential areas for improvement.

Depending on the regulatory and future repurposing plans of this ex-industrial site, specific remediation techniques, if needed, will be selected (**IAEA, 2004b; Liu et al., 2018**). If the decision to urbanise this site is reached, the problem of constructing buildings on ash and slag (in geotechnical sense) will arouse. Also, there will be the problem of removal and re-depositing of the material excavated during construction since a new location for the NORM residues has to be found, accepted by the regulator and used for this material. No agricultural plans for this location exist so far, therefore radionuclide contamination should not be a problem in the sense of the cultivation of edible plants for the pure greening purposes of the site. The probable future of the site will include the construction of buildings in the back of the location (north inland) and landscaping the location (marked on **Figure 3** as zone "D") by planting bushy plants and small trees, forming a promenade, etc., or constructing a photovoltaic power station (solar park). One of the ideas was to use the location partly as a marina for smaller vessels, which has been abandoned. Due to the contemporary narrative concerning renewable energy sources, a solar park has a future at this site, which would include applying a layer of soil to certain parts of the location and covering certain parts with concrete, as well as other similar operations recommended by a risk assessment study which is to be done specifically for a given remediation or construction plan.

6. References

Anderson, K. D., Arora, R., & Benson, J. (2001). Achieving Brownfields Clean Up at a Radium-Contaminated Site. *Soil and Sediment Contamination: An International Journal*, 10 (4), 423–437. https://doi.org/10.1080/20015891109356

Berc, LJ. (2023): The Physical Planning Information System. Željeznice, 21, 4/2023.

Boott, R., Heppell, K., Haklay, M., & Morley, J. G. (2001). The use of GIS in Brownfield redevelopment. In: Geographical Information Science Research Conference 2000 (GISRUK'00), 5-7 April, 2000, University of York.

Brebbia C. A. and Mander, U. (2006). Brownfields III: Prevention, Assessment, Rehabilitation and Development of Brownfield Sites. 288 p., Wit Press, Southampton, UK.

CBS (2023). Statistical information 2023. Report, Croatian Bureau of Statistics, ISSN 1330-335X [in Croatian].

CBS (2024). Tourist Arrivals and Overnight Stay in 2023. Report TUR-2023-1-2, Croatian Bureau of Statistics, ISSN 1334-0557 [in Croatian].

Demers, M. N. (1997). Fundamentals of Geographic Information Systems. 1st ed. Wiley.

Dragović, S., Mihailović, N., & Gajić, B. (2008). Heavy metals in soils: Distribution, relationship with soil characteristics and radionuclides and multivariate assessment of contamination sources. *Chemosphere*. 72, 491-495. doi: 10.1016/j.chemosphere.2008.02.063

Dulić, O. and Krklješ, M. (2013). Brownfield Sites - Environmental Effects of Their Revitalization. International Eco-Conference "Environmental Protection of Urban and Suburban Settlements", Novi Sad

EPA (1989). Risk Assessments Methodology – Environments Impact Statement NESHAPS for Radionuclides. United States Environmental Protection Agency, EPA/520/1-89-005.

Ester, Z., Dobrilović, M., & Janković, B. (2005): Dual Method of Demolition Industrial Buildings by Blasting, Performed Above Aqueduct Protected by UNESCO. Proceedings of the 3rd World Conference on Explosives & Blasting, Brighton, UK, 13-16. 9., 159-165

García, S., Luengo, J. & Herrera, F. (2015). Data Preprocessing in Data Mining. Springer, 320 p., https://doi.org/10.1007/978-3-319-10247-4

Getaldić, A., Surić Mihić, M., Veinović, Ž., Skoko, B. & Petrinec, B. (2023). Remediation of coal ash and slag disposal site: Comparison of radiological risk assessments. Rudarsko-geološko-naftni zbornik, 38 (3), 95–104. https://doi.org/10.17794/rgn.2023.3.8

Gribov, A. and Krivoruchko, K. (2020). Empirical Bayesian kriging implementation and usage. *Science of Total environment, Volume* 722, 20 June 2020, 137290. https://doi.org/10.1016/j.spasta.2019.100368

Hollander, J., Kirkwood, N., & Gold. J. (2010). Principles of Brownfield Regeneration Cleanup, Design, and Reuse of Derelict Land, 152 p., Island Press, Washington, USA

IAEA (2004a). Remediation of Sites With Dispersed Radioactive Contamination, Technical Reports Series No. 424, IAEA, Vienna, Austria

IAEA (2004b). Soil Sampling for Environmental Contaminants. International Atomic Energy Agency, IAEA--TECDOC-1415, Vienna, Austria.

IAEA (2013). Management of NORM Residues, IAEA--TECDOC-1712, IAEA, Vienna, Austria.

IAEA (2022). Management of Naturally Occurring Radioactive Material (NORM) in Industry, Proceedings Series - International Atomic Energy Agency, Vienna, Austria.

IAEA (2024). Holistic Approach to Management of Naturally Occurring Radioactive Material (NORM), IAEA-TECDOC-2071, IAEA, Vienna, Austria.

Ippolito, A., Selim, Y., Tajani, F., Ranieri, R., & Morano, P. (2023). A GIS Referenced Methodological Approach for the Brownfield Redevelopment. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol 14109. Springer, Cham. https://doi.org/10.1007/978-3-031-37120-2_30

Koduru, S. K. R. (2022). A Comprehensive Analysis of Normalization Approaches for Privacy Protection in Data Mining. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 8 (5) 144-157. https://doi.org//10.32628/CSEIT1228529

Krivoruchko, K. and Gribov, A. (2019). Evaluation of empirical Bayesian kriging. *Spatial Statistics* Vol 32 (2019) 100368. https://doi.org/10.1016/j.scitotenv.2020.137290

Lauer, N. E., Hower, J. C., Hsu-Kim, H., Taggart, R. K., & Vengosh, A. (2015) Naturally Occurring Radioactive Materials in Coals and Coal Combustion Residuals in the United States 2015 https://sites.nicholas.duke.edu/avner-vengosh/files/2011/08/NORM-in-coal-and-coal-ash_EST1.pdf

Lillesand, T. M., Kiefer, R. W., & Chipman, J. W. (2004). Remote sensing and image interpretation (5th ed.). John Wiley & Sons.

Liu, L., Li, W., Song, W., & Guo, M. (2018). Remediation techniques for heavy metal-contaminated soils: Principles and applicability, *Science of The Total Environment*, Vol. 633, 206-219, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2018.03.161

Longley, P. A., Goodchild, M. F., Maguire, D. J., & Rhind, D. W. (2005). Geographic information systems and science (2nd ed.). John Wiley & Sons.

Macenić, M., Kurevija, T., & Medved, I. (2020). Novel geothermal gradient map of the Croatian part of the Pannonian Basin System based on data interpretation from 154 deep exploration wells. Renewable and Sustainable Energy Reviews. 132 (2020) 110069. https://doi.org/10.1016/j.rser.2020.110069

Matković, I. and Jakovčić, Martina. (2019). Brownfield Areas and their Regeneration: Definitions and Approaches. Prostor. 27. 348-359. 10.31522/p.27.2(58).13. [in Croatian].

Megharaj M. and Naidu R. (2017). Soil and brownfield bioremediation. *Microb Biotechnol*. 2017 Sep;10 (5):1244-1249. doi: 10.1111/1751-7915.12840. Epub 2017 Aug 22. PMID: 28834380; PMCID: PMC5609233.

Obaje, S. O., Ogunyele, A. C., Adeola, A. O., & Akingboye, A. S. (2019). Assessment of stream sediments pollution by potentially toxic elements in the active mining area of Okpella, Edo State, Nigeria. Rudarsko-geološko-naftni zbornik, 34 (2). https://doi.org/10.17794/rgn.2019.2.5

Official Gazette (2014). The Radioactive Waste, Disused Sources and Spent Nuclear Fuel Management Strategy. Narodne novine, Nr. 125 [in Croatian].

Official Gazette (2018). Decision of Croatian Government on the adoption of the National Programme for implementation of strategy of radioactive waste, disused sources and spent nuclear fuel management (Programme till 2025 with glance till 2060). Narodne novine, Nr. 100 [in Croatian].

Popović, A. and Đorđević, D. (2009). pH-Dependent Leaching of Dump Coal Ash – Retrospective Environmental Analysis. *Energy Sources*. Part A. 1553-1560. 10.1080/15567030802094003.

Prlić, I. (2011a). Implementation of radiological investigative works in the City of Kaštela at the location of the former Jugovinil factory and its surroundings, final report of the project - volume I, IMI & FZOEU [in Croatian].

Prlić, I. (2011b). Radiological measurements in the City of Kaštela at the location of the former Jugovinil factory and its surroundings, final report of the project - volume II, IMI & FZOEU [in Croatian].

Prlić, I. (2011c). Calculation of the volume of coal slag and ash located in the City of Kaštela at the location of the former Jugovinil factory and its surroundings, final report of the project - volume III, IMI & FZOEU [in Croatian].

Prlić, I. (2011d). Research of documentation important for the implementation of radiological investigation works in the City of Kaštela at the location of the former Jugovinil factory and its surroundings, final report of the project - volume IV, IMI & FZOEU [in Croatian].

Radas, T. (2024): Primjena GIS tehnologije u kartiranju prirodnih radionuklida (*Application of GIS technology in mapping natural radionuclides*). Diplomski rad, Rudarsko-geološko-naftni fakultet Sveučilišta u Zagrebu, Zagreb, 38 str. (*in Croatian – English abstract*)

Schrooten, P. and Van Alphen, A. (2008). GEMS: GIS and geo-statistics integrated in Brownfield remediation and redevelopment, applied in the Vilvoorde region. 55-64. 10.2495/BF080061.

Segner, H., Schmitt-Jansen, M., & Sabater, S. (2014). Assessing the Impact of Multiple Stressors on Aquatic Biota: The Receptor's Side Matters. *Environmental Science & Technology* 2014 48 (14), 7690-7696 DOI: 10.1021/es405082t

SFRY (1974). Decision of Republic Secretariat for National Health and Social Protection - Sanitary Inspectorate concerning the permanent disposal of uranium ore tailings in the grounds of the "Jugovinil" factory in the Kaštel Gomilica. Ref.No. UP-I-05-110/1-1974, February 22nd 1974, Zagreb [in Croatian].

Skoko, B., Radić Brkanac, S., Kuharić, Ž., Jukić, M., Štrok, M., Rovan, L., Zgorelec, Ž., Perčin, A., & Prlić, I. (2023). Does exposure to weathered coal ash with an enhanced content of uranium-series radionuclides affect flora? Changes in the physiological indicators of five referent plant species, *Journal of hazardous materials*, 441, 129880, 14, doi:10.1016/j.jhazmat.129880.

Syms, P. (2012). Principles of Brownfield Regeneration. *Journal of Urban Design*, 17 (2), 307–308. https://doi.org/10.1080/13574809.2012.666183

Tokonami, S. and Ishikawa, T. (2007). Radiological Aspects of Using Coal Ash (Slag) in the Building Industry. Japanese *Journal of Health Physics*, 2007, Volume 42, Issue 3, Pages 227-233, Released on J-STAGE August 05, 2010, Online ISSN 1884-7560, Print ISSN 0367-6110, https://doi.org/10.5453/jhps.42.227,

Veinović, Ž., Prlić, I., Kujundžić, T., Surić Mihić, M., Perković, D., Domitrović, D., Korman, T., Mostečak, A., & Uroić, G. (2020). Gospodarenje reziduima u okviru Nacionalnog programa provedbe Strategije zbrinjavanja radioaktivnog otpada, iskorištenih izvora i istrošenog nuklearnog goriva Republike Hrvatske. Kemija u industriji : časopis kemičara i tehnologa Hrvatske, 69 (2020), 3-4; 163-174. doi: 10.15255/KUI.2019.043

Zheng B., and Masrabaye F. (2023). Sustainable brownfield redevelopment and planning: Bibliometric and visual analysis. *Heliyon* 2023 Jan 26; 9(2):e13280. doi: 10.1016/j.heliyon.2023.e13280. PMID: 36816311; PMCID: PMC9929300.

SAŽETAK

Primjena GIS tehnologije u gospodarenju *brownfield* lokacijama na kojima se nalaze rezidui

Budući da su *brownfield* lokacije jedan od glavnih problema inženjerstva zaštite okoliša, zemlje Europske unije obvezne su razmotriti gospodarenje tim lokacijama. Jedan od glavnih alata za upravljanje *brownfield* lokacijama jest GIS tehnologija, primijenjena na dvjema razinama: prikaz svih BFS-ova u državi i prikaz distribucije materijala/zagađivala (površina, količina i koncentracije itd.) za određene lokacije. Republika Hrvatska ima nekoliko *brownfield* lokacija uključujući onu bivše tvornice plastike i kemijskih proizvoda Jugovinil, Grad Kaštela, Hrvatska, kao dobar primjer. Industrijsko postrojenje koje je prestalo s radom i njegova elektrana na ugljen izazvale su kontaminaciju teškim metalima i reziduima (industrijskim djelovanjem koncentrirani prirodno radioaktivni materijali). Od zatvaranja tvornice, druge, manje industrijske aktivnosti (brodogradilišta) uzrokovale su dodatno onečišćenje lokacije teškim metalima. Ova lokacija ima nekoliko zona na kojima se nalazi ukupno 552 101,29 m^3 ugljenoga pepela i šljake iz bivše termoelektrane, navezenoga mineralnog materijala i građevinskoga otpada, od kojih je ≈ 240 893 m^3 relevantno za ovaj rad. Ovdje prikazano istraživanje temelji se na izvješćima o studijama provedenim 2010. – 2011. Budući da je količina podataka dobivena istraživanjem na lokaciji iznimno velika, u ovome radu prikazan je samo dio njih: mjerenja koncentracija triju radionuklida iz radioaktivnoga niza Th-232. Računalnim GIS programom ArcGIS Pro izrađene su karte koncentracija radionuklida, što je omogućilo prepoznavanje područja većih koncentracija i potencijalnih izvora onečišćenja. Interpolacija je provedena geostatističkom metodom *Empirical Bayesian Kriging*. Preporučeni postupci za upravljanje ovom lokacijom uključuju sanaciju i upućuju na oprez u slučaju planiranja urbanizacije ove lokacije.

Ključne riječi:
brownfield, rezidui, radionuklidi, GIS

Author’s contribution

Želimir Veinović (associate professor): conceptualisation, formal analysis, investigation, validation and supervision. **Dario Perković** (associate professor): conceptualisation, software, methodology, visualisation, supervision. **Tonka Radas** (mag. geol.): software, visualisation. **Ivica Prlić** (DSc): data curation, resources, investigation, methodology, validation and supervision.
All authors have read and agreed to the published version of the manuscript.